(2)

TIP VORTICES IN UNSTEADY FLOWS

(Original Title: "Experimental Study of Cavitation Inception")

Contract N00167-85-K-0165

[redacted]

Final Report

TIP VORTICES IN UNSTEADY FLOWS

(Original Title: "Experimental Study of Cavitation Inception")

Contract N00167-85-K-0165

For the period

October 2, 1985 – January 4, 1992

$491,710

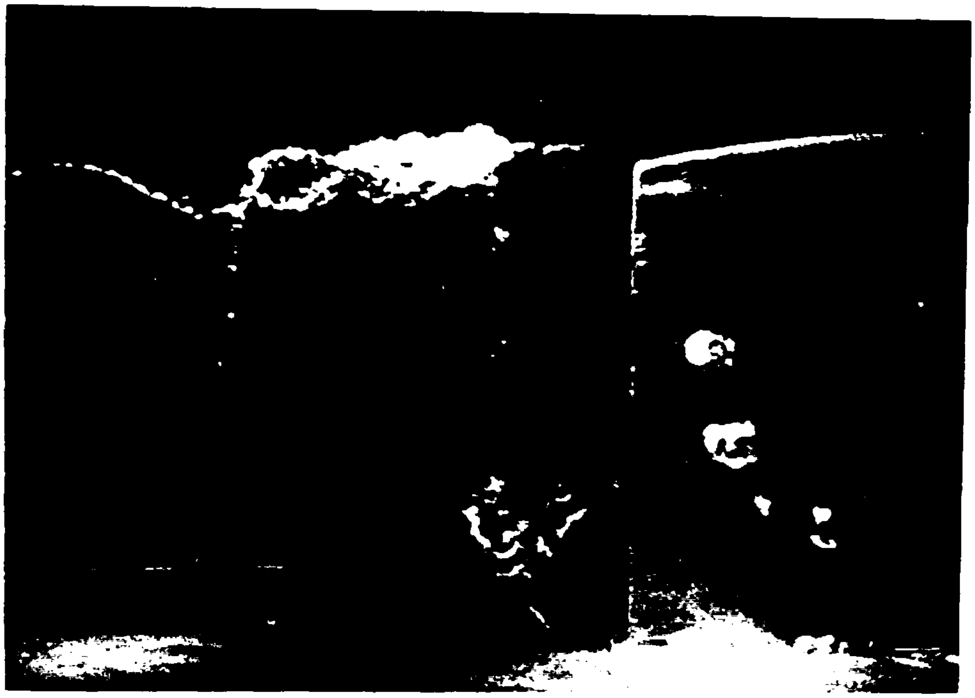
Prepared by

Allan J. Acosta and Anthony Leonard

Division of Engineering and Applied Science

California Institute of Technology, Pasadena, CA 91125

April 20, 1992 – Report No. Eng. 183.18



Photograph of tip vortex cavitation downstream of a hydrofoil oscillating at a high reduced frequency, $k = 2.4$. Cavitation initiates in the knee of the vortex formation where the tip vortex links with the spanwise vortex formed when the hydrofoil is at the minimum angle of attack in an oscillation cycle. Cavitation rapidly spreads into the tip vortex region between the spanwise vortex formed at the minimum angle of attack of the hydrofoil and the spanwise vortex formed at the maximum angle of attack of the hydrofoil in an oscillation cycle($Re = 12\times10^5$, $\alpha = 5^O$, $\triangle\alpha = \pm5^O$, $k = 2.4$).

Introduction: This report describes in brief the activities of our research in, first, cavitation inception, and then, second, tip vortex problems in steady and unsteady flows. There are two components of this work. The first is an experimental study of cavitation inception and cavitation nuclei determination in a variety of laboratory and natural settings. Cavitation and cavitation inception are important aspects of the complex flow associated with propulsion in the ocean environment. Two specific features of this flow were addressed in a long series of reports and publications listed at the end of this report. These features are (1) cavitation inception processes in a large scale turbulent shear flow and (2) cavitation inception and the structure of trailing tip vortices in first steady and then unsteady flows. Finite aspect ratio hydrofoils were used in both studies; the latter unsteadiness was achieved by oscillating the foil in pitch of a point 35% of the chord from the leading edge. A special feature of this unsteady foil work is that the experimental part was carried out in close collaboration with a computational componenent led by one of us (A. Leonard). This work has the special feature that it is based on vorticity elements and their transport, thus no additional computation is needed in regions devoid of vorticity (except for dependent variables such as velocity when that is desired). The complexity of the unsteady shed three-dimensional vortex wake was initially most surprising and it was extremely helpful to be able to visualize this flow. The computational effort is now being continued in a separate effort and the experimental work is being concluded in a separate contractual effort (ONR Grant N00014-92-J-1189).

Discussion: There are roughly two dozen publications, theses and reports listed which were supported wholly or in part under the present contract effort. It is useful here to separate them into several groups as follows: I, Shear Flow and Cavitation; II, Nuclei and Nuclei Measurement; III, Tip Vortices; IV, Miscellaneous; V, Computation.

The first of these, I, is the conclusion to a long series of experiments on cavitation and nuclei in separated flows and jets and items 1, 2, and 17 belong to group I. There were some unexpected findings here new to the shear flow community and to us; namely, that cavitation inception occurred *first* in the secondary flow structures in the shear flow downstream of a bluff two-dimensional plate held normal to the flow. The dramatic feature of the flow of course was the intense and noisy cavitation seen in the spanwise nearly two-dimensional periodic vortices shed in the wake behind the plate. That cavitation occurred first in the secondary flow structure was subsequently attributed to the small size of these vortices; it may be recalled that these more-or-less longitudinal vortices are actually part of a vortex loop connected to the periodically shed spanwise vortices.

Cavitation nuclei and their measurement has long been a major concern of the hydrodynamic community and it remains so even up to today. In our laboratory work we have emphasized the observation and quantification of microbubbles (a "good" nucleation source for cavitation) and microparticulates (which may lead to cavitation) is essential in cavitation research *and* testing. For this purpose we have used Fraunenhofer holography to reconstruct the microbubbles and particulates found in our water tunnel. In the shear flows studied there was a general agreement between the number of cavitation events that occur and the number of nuclei available to cause the cavitation. Holography or, more particularly, the subsequent reconstruction and tedious analysis required to document the distribution of nuclei sizes and classification (microbubble or particulate) has led many groups to devise a special test device to categorize the extent of nucleation present in the test water or natural water. That is, a special device to test the "susceptability" of the fluid to cavitate is used rather than the direct measurement of holography. A Venturi tube or Venturi tube modified by inserting a central plug into the flow has been the device of choice. But there have been real difficulties in correlating the results of such tests with carefully measured actual distributions by holography. The publications in group II (items, 3, 4, 5, 7, 14, 21, 22, 23, 25) all deal carefully with the issues. The general conclusion that the cavitation event rates determined in Venturi devices, generally and specifically the ones used by d'Agostino, do not agree with what would be expected from holographic nuclei measurement of the undisturbed test fluid with the Venturi device results implying fewer nuclei (perhaps by an order of magnitude) and of smaller size. This is too bad as the Venturi is a much simpler device to use than the holographic one; the more recent plug-Venturi devices claim a superior performance to a simple Venturi tube but thus far independent assessment of these claims is not available. In the meantime Phase Doppler Anemometry appears to have promise to measure micro*bubble* distributions if there are not too many solid particulates present.* These issues have an important bearing on the design of test facilities and at the same time point out that *extremely little* is known about nuclei of the natural oceanic environment. It was for that reason that items 2 and 4 were undertaken; it is to be hoped that further work along these lines will be undertaken in the future for the good of the field.

Trailing tip vortices are treated in group III (items 8, 9, 10, 11, 12, 13, 18, 20). These vortices are important, noticeable features of all hydrofoil-driven propulsive systems and in liquid flows are often the source of cavitation inception. And for that reason this topic has received much attention in the Naval Hydrodynamic community. Our own contribution has focussed on some little-reported aspects of these trailing vortices; namely, in a detailed study of the velocity distribution and even pressure within the vortex core itself (Ref. 20). There we observe a local flow unsteadiness of a surprising intensity which seems to us to be a feature of the tip vortex flow and *not* that of the set-up or tunnel flow. As a side light (Ref. 11), we explored the possibility of greatly modifying the tip vortex flow and its tendency to cavitate by equipping the foil tip with a small ring wing; this ring nearly completely suppressed the tip vortex cavitation and, in a subsequent experiment by Prof. Green and his student Duan (Ref. 24), it was shown that there was no drag penalty for the ring wing addition for moderate lift coefficients.

By far the most unexpected findings were the complex (and still incompletely understood) vortex structure developed by the finite aspect ratio hydrofoil (see the frontis piece). This work (group III, items 16, 17) is still continuing under grant No. N00014-92-J-1189 and should be completed in the present calendar year.

Additional incidental work is found in group IV (items 15, 19).

In our computation work (group V, item 26) we have concentrated on the development of vortex methods to simulate the unsteady hydrofoil flows being investigated experimentally. A new two-dimensional algorithm allows very high resolution simulations of time-dependent surface pressures and spanwise vortex structures in the near wake away from the tip region. This work is continuing and is being extended to three-dimensions under grants No. N00014-92-J-1189 and No. N00014-92-J-1072. An alternative compu-

* Dr. M. L. Billet, personal communication

tational scheme using three-dimensional vortex tubes with variable internal structure was developed. Its application to the unsteady hydrofoil flows is being pursued under grant No. N00014-92-J-1189.

People: Dr. T. J. O'Hern is now a staff engineer at Sandia Corporation; Dr. S. I. Green is Assistant Professor of Mechanical Engineering at the University of British Columbia, Vancouver, B.C.; Dr. L. d'Agostino is now Assistant Professor of Aerospace Engineering at the University of Pisa, Italy; Mr. D. P. Hart and Mr. P. Koumoutsakos are expected to complete their Ph.D. studies this summer. Mr. Inki Min is in his second year of Ph.D. research.

List of Publications, Theses and Reports

1. Cavitation Observations in a Turbulent Shear Flow. T.J. O'Hern and A.J. Acosta, 21st Am. Tow Tank Conf., National Acad. Sci, August 1986.

2. Cavitation Inception Scale Effects: Part I, Inception in a Shear Layer: Part II, Nuclei Distributions in Natural Waters. 1986. Ph.D. Thesis, T. J. O'Hern, California Institute of Technology, Division of Engrg. & Applied Science.

3. Studies in Cavitation Bubble Dynamics, Part I: A Cavitation Susceptibility Instrument; Part II: The Dynamics of Cavitation Bubbly Flows. 1987. Ph.D. Thesis by L. d'Agostino, California Institute of Technology, Division of Engineering & Applied Science.

4. Comparison of Holographic and Coulter Counter Measurements of Cavitation Nuclei in the Ocean. 1988. by T.J. O'Hern, L. d'Agostino, A.J. Acosta. J. Fluid Engineering, 110, pp. 200-207.

5. A Cavitation Susceptability Meter with Optical Cavitation Monitoring. 1987. L. d'Agostino and A.J. Acosta. International Towing Tank Conference, Tokyo.

6. Cavitation Inception in a Turbulent Shear Flow. 1988. T.J. O'Hern. Joint AIAA/ ASCE/ASME/SIAM/APS First National Fluid Dynamics Congress. July 1988, Cincinnati.

7. Comparison of a Cavitation Susceptability Meter and Holographic Observation for Nuclei Detection in Liquids. 1988. L. d'Agostino, T. Pham, S. Green, First National Fluid Dynamics Conference, also J. Fluids Engineering, 111, pp 197-203, June 1989.

8. The Influence of Tip Geometry on Trailing Vortex Rollup and Cavitation. S.I. Green, A.J. Acosta, R. Akbar. First National Fluid Dynamics Conference, 1988.

9. An Exploratory Study of Reynolds Number Effects on Trailing Vortex Core Unsteadiness. S.I. Green. AIAA Paper No. 88-3622, First National Fluid Dynamics Conference, 1988.

10. Three Tip Vortex Examination Techniques. Sheldon Green. ASME Symp. on Multiphase Flow and Cavitation. O. Furuya (Ed.), 1987.

11. Tip Vortices – Single Phase and Cavitating Phenomena. S.I. Green. California Institute of Technology Technical Report Eng. 183-17, 1988.

12. Tailored Air Bubble Determination of Trailing Vortex Core Pressure. S.I. Green. Cavitation and Multiphase Flow Forum, ASME, ed. O. Furuya. 1989.

13. Correlating Single Phase Flow Measurements with Observations of Trailing Vortex Cavitation. S.I. Green, Journal of Fluids Engineering, 113, pp 125-129, March 1991.

14. Comparison of a Cavitation Susceptibility Meter and Holography for Nuclei Detection in Liquids. L. d'Agostino, T. Pham, S. Green, Journal of Fluids Engineering, June 1989 vol 111, pp 197-203.

15. Cavitation Inception. A.J. Acosta. Remarks in Proceedings of the U.S.-Romanian Workshop on Water Resources Engineering, Bucharest 1989.

16. Observations of Cavitation on a Three-Dimensional Oscillating Hydrofoil. D. Hart, A.J. Acosta, C.E. Brennen. Symposium on Cavitation and Multiphase Flows, O. Furuya (ed.), ASME, June 1990.

17. An Experimental Investigation of Turbulent Shear Flow Cavitation. T.J. O'Hern. J. Fluid Mech. 1990, vol. 214, pp 365-391.

18. Cavitation Inception in the Tip Vortex Region of an Oscillating Three- Dimensional Hydrofoil. D.P. Hart. First Joint ASME/JSME Fluids Engineering Conference, June 1991.

19. Cavitation and Cavitation Types. A.J. Acosta. Chapter 2 of the book *Cavitation of Hydraulic Machinery*, (H. Murai, ed). Intl. Book Series on Hydraulic Machinery, Tower Tech Press, England (to appear).

20. Unsteady Flow in Trailing Vortices. S.I. Green and A.J. Acosta. 1991. Journal of Fluid Mechanics, Vol. 227, pp. 107-134.

21. A Cavitation Susceptability Meter with Optical Cavitation Monitoring - Part One: Design Concepts. L. d'Agostino, A.J. Acosta. J. Fluids Engineering, 113, pp. 261-270, June 1991.

22. A Cavitation Susceptability Meter with Optical Cavitation Monitoring - Part Two: Experimental Apparatus and Results. L. d'Agostino, A.J. Acosta. J. Fluids Engineering, 113, pp. 270-278, June 1991.

23. Separation and Surface Nuclei Effects in a Cavitation Susceptability Meter. L. d'Agostino, A.J. Acosta. J. Fluids Engineering, 113, pp 695-700, December 1991.

24. Lift-Drag Performance of Conventional and Ducted Wing Tips. S.Z. Duan, S.I. Green, A.J. Acosta. ASME Polyphase Flow and Cavitation Forum, June 1992 (to appear).

25. Simultaneous Cavitation Susceptability Meter and Holographic Measurements of Nuclei in Liquids. L. d'Agostino and S.I. Green, J. Fluids Engineering (to appear).

26. Lagrangian Simulation of Concentrated Vortex Structures, A. Leonard, Proc. of 4th Intl. Symp. on Comput. Fluid Dyn., Sept. 9-12, 1991, U. of Calif. Davis, Vol. I, p. 682.